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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

The Hardening and Tempering of Steel—Conventional and Hot Oil Quenching

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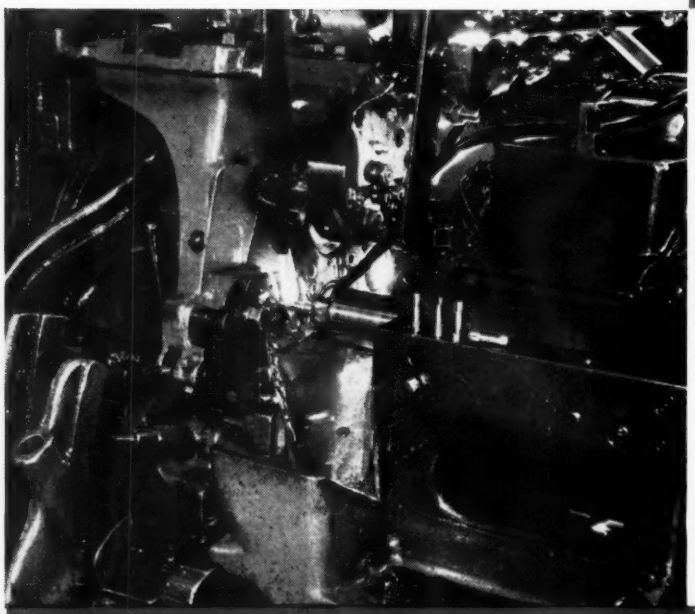

PART

Over-all Length . 1"
Stock Diameter . 5/16"
Slot . . . . . 1/4" deep x 5/16"
Head . . . . . 5/16" dia. x 3/16" long
Small Diameter . 1/4" x 23/32" long
Milled Flats . . . 5/32" wide on 23/32 dia.

TOOLING

Davenport 5-spindle Model B

1st position . . . Form and Support
2nd position . . . Size (shaving tool) and Support
3rd position . . . Mill slot (Slotting saw 965 r.p.m. 2 1/4", 560 s.f.p.m.
4th position . . . Mill flats and Support
5th position . . . Radius, chamfer, cut-off (Cut-off tool .0025" feed)

DATA

Material B-1113
Cycle . . . . . 3 seconds
Spindle speed . . . . . 1,930 r.p.m.

875 MORE PIECES per 8-hr. shift

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The Hardening and Tempering of Steel—Conventional and Hot Oil Quenching

HEAT TREATING operations consist of heating and cooling metals and alloys in order to produce the optimum combination of mechanical and chemical properties for a specific service. In a given steel, the desired results are obtained by changing the form in which carbon is dispersed in iron. Annealing, normalizing, hardening, and tempering are common heat treating operations for steel. Full annealing, normalizing, and hardening (quenching) involve heating steel above the critical temperature range, described later, while process annealing and tempering involve heating below the critical temperature range. In these operations slow or rapid cooling follows heating as is necessary.

UNTREATED higher carbon steels are almost as useless as raw crude oil. Both have possibilities for use which can only be developed by further treating to bring out the required desirable properties which sometimes make the treated steel as valuable as higher alloys, which are more expensive and difficult to make.

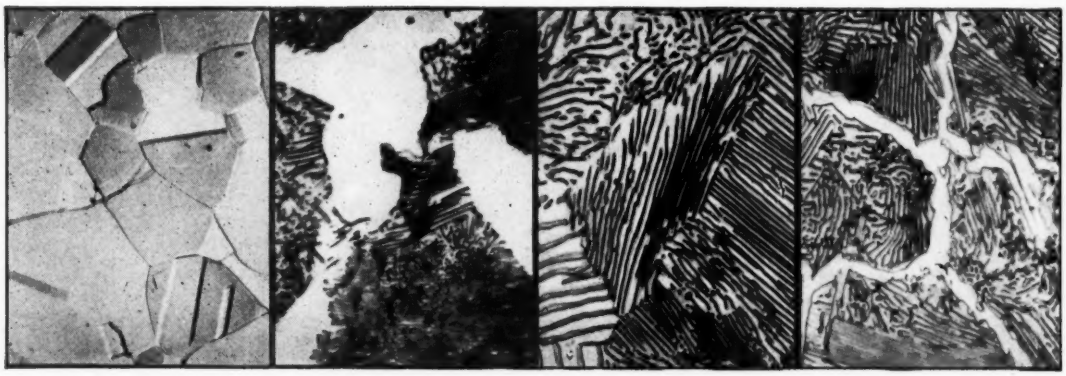
One of the most interesting methods of heat treating being presently used is a hot quenching process known as hot oil quenching or marquenching. The process involves quenching red hot steel in mineral oil at 200-400°F., holding for temperature equalization and then cooling to ordinary temperatures, usually in air. While present commercial use of hot oil quenching is limited primarily to the automotive, ball bearing and tool industries, it is expected that the use will spread in the near future to aeronautical and other industries. As a matter of economics, hot oil quenching is particularly important today because it makes possible some substitution of the more plentiful carbon steels for the relatively scarce and expensive high alloy steels.

Plain carbon steels are defined in metallurgy as alloys of iron and carbon, while alloy steels contain additional elements such as nickel, chromium, vanadium, and molybdenum. A brief summary of the pertinent phase transformations in the structure of iron-carbon alloys will provide the basis for describing changes which occur on rapid cooling. These relations also facilitate comparisons of plain carbon and alloy steels and are of value in emphasizing the utility of properly heat-treated carbon steels.

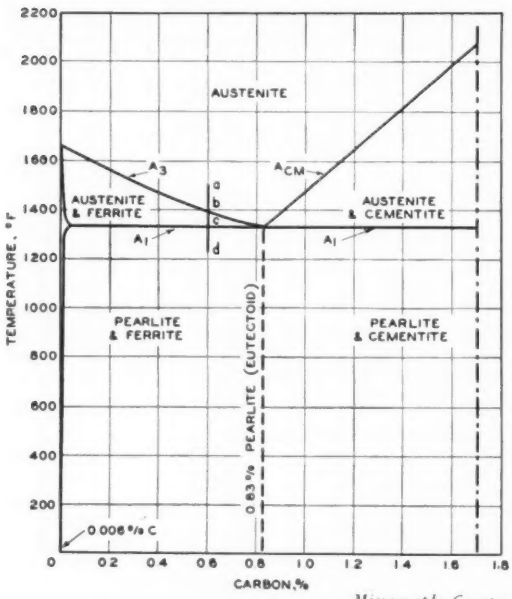
CONSTITUTION DIAGRAM

The section of the iron-carbon constitution diagram concerned in heat-treating steels is shown in Figure 1. Phase transformations occur in the solid state on heating and cooling steel and involve changes in basic crystal structure and properties. This diagram shows the areas, with respect to temperature and carbon content, in which various phases are present.

The phase and structural changes on heating or cooling may be conveniently demonstrated by tracing the cooling of a typical steel. (Identical changes would occur in the reverse order on heating.) At 1500°F. the 0.6% carbon steel represented by point "a" has an austenitic structure. Austenite is a solid solution, analogous to a liquid solution,



Austenite 500X | Pearlite and Ferrite — 0.6% Carbon — 1000X | Pearlite-Isothermal Transformation at 1300°F.— 0.9% Carbon — 1000X | Pearlite and Cementite (Carbide) — Carburized Case — 1000X



Micrographs Courtesy United States Steel Company Research Laboratory

Figure 1 — Section of Iron-Carbon Constitution Diagram Concerned in Heat-Treating Steel.

of iron carbide in iron of a definite crystal structure, called gamma iron.

On cooling the 0.6% carbon steel, a phase transformation occurs at point "b". At this point gamma iron changes in crystal structure and a new form, alpha iron containing a small amount of carbon and called ferrite, is rejected from the solid solution. Ferrite is soft, ductile and tough. With further cooling the remaining austenite becomes richer in carbon and increasing quantities of ferrite are rejected from the solid solution. At point "c" the residual austenite of 0.83% carbon, termed "eutectoid composition", transforms into a lamellar aggregate of ferrite and carbide known as pearlite.

Alloys containing 0.006 to 0.83% carbon are designated as hypoeutectoid steels, while alloys of 0.83 to 1.70% carbon are called hypereutectoid steels. The changes on cooling hypereutectoid steels are quite similar to those described above: at line A_{cm}, corresponding to line A_3 for hypoeutectoid compositions, a new structure, cementite, separates out of the austenite solid solution. Cementite is iron carbide and is the hardest and most brittle constituent in steel. These phase changes, referred to as the A_3, A_1, and A_{cm} transformations, occur at lower temperatures on cooling than during heating. The temperature ranges between A_1 and A_3 or A_1 and A_{cm} are called the critical temperature ranges. The characteristic structures described above are readily identified under the microscope. Several micrographs are presented in Figure 1.

TIME-TEMPERATURE TRANSFORMATIONS

Steels of great engineering importance can be obtained by accelerating the cooling rate so that structures other than the structures described above are produced by hardening. The scientific basis of hardening was established by E. S. Davenport and E. C. Bain in their paper "Transformation of Austenite at Constant Subcritical Temperatures", (Trans. AIMME, *90*, 1930). After rapidly cooling austenitic steel, they followed the progress of the isothermal transformation experimentally. Figure 2 illustrates typical results which might be obtained for one steel in this manner. This relation is variously termed an S-curve, isothermal transformation diagram, or a time-temperature transformation diagram. For any constant temperature, it shows the time required for transformation to begin and end.

After slowly cooling to a constant temperature just below A_1, a relatively long time is required for the isothermal transformation to begin. Coarse lamellar pearlite, which is soft and relatively ductile, is the principal product. Ferrite or carbide will also be precipitated in this region for hypoeutectoid or

hypereutectoid steels, respectively.

A faster cooling rate to about 1000°F., to the "knee" of the S-curve, reaches a region of minimum holding time before the isothermal transformation begins. At this point no ferrite or carbide is precipitated (except for some ferrite from very low carbon steels). Fine lamellar pearlite, which has become harder, stronger, and less ductile as the transformation temperature decreased, is produced.

Cooling at still higher rates through a temperature, M_s, produces the hardest and least ductile transformation product of austenite, known as martensite. Martensite is considered to be a supersaturated solid solution of carbide in alpha iron. This structure is unstable, and, unlike pearlite or cementite of definite chemical composition, its composition varies with the carbon content of the steel. It is worth noting that harder martensite forms from steel of higher carbon content. The M_f temperature, finish of martensite transformation, is identified in Figure 2 along with the M_s temperature, start of martensite transformation.

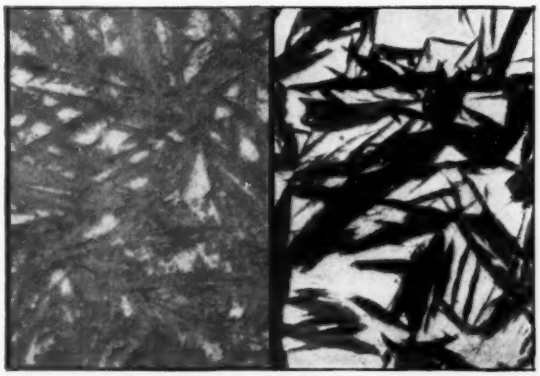
Isothermal transformation products obtained at temperatures between the fine pearlite and martensite ranges are called bainite, a structure which is also intermediate in properties to these former products. Frequently an obvious distinction between "upper" and "lower" bainite is made.

Micrographs of martensite and bainite are shown in Figure 2.

With the exception of the martensite transformation, it is indicated that all of these transformations proceed by processes of crystal nucleation and growth. They are time-temperature dependent and in alloys involve diffusion and phase changes.

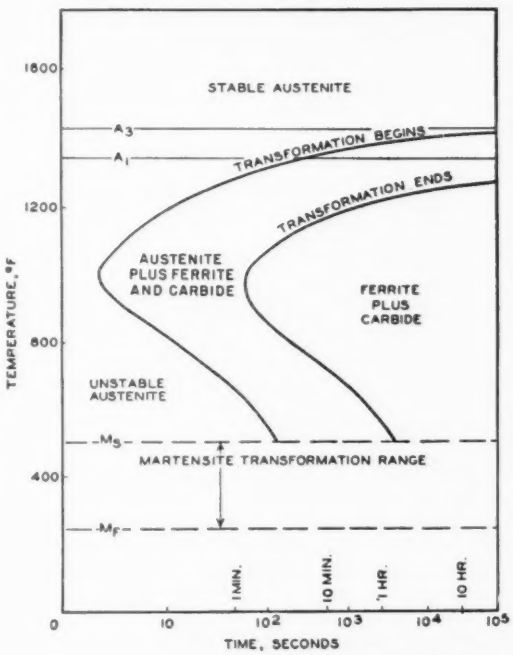
Since martensite has the same chemical composition as the parent austenite, a composition change or diffusion is not involved in this transformation. It is also believed that no crystal nucleation and growth are involved. On rapidly cooling austenite into the martensite transformation range, martensite begins to form instantly at the M_s temperature, accompanied by sudden crystal structure changes in the austenite. For a definite decrease in temperature, the amount of martensite formed is small just below M_s, but it then increases until near the end of the transformation, when it again becomes small. The fact that the martensite transformation ceases if cooling is interrupted clearly shows that it is dependent on temperature only, being independent of time. The severe cooling and the increased volume of martensite as compared with austenite results in thermal and transformation stresses in the piece: this accounts for the unstable nature of martensite.

Hardenability refers to the ability of a steel to harden when cooled from above the critical temperature. Any factor that tends to displace the S-curve knee to the right, or increases the minimum



Martensite — 0.9% Carbon — 1000X

Austenite Half Transformed to Bainite at 550°F. — 0.9% Carbon — 2500X



Micrographs Courtesy United States Steel Company Research Laboratory

Figure 2 — Time-Temperature Transformation Diagram.

holding time before transformation begins, increases hardenability or decreases the critical cooling velocity. The *critical cooling velocity* is the minimum cooling rate, roughly measured at the S-curve knee, that causes "full hardening" of steel to martensite. In other words, the holding time at the S-curve knee must allow the quench to remove heat in less time than is required for transformation to begin at this temperature. The chief factors affecting hardenability are the austenite composition and the austenitizing conditions. It is worth noting that increased cooling velocity beyond the critical rate does not decrease M_s or suppress the

martensite transformation. The critical cooling velocity varies widely for different steels. It is very high for low carbon steel (0.1-0.3%C) and is very low for high alloy steel — in fact, furnace cooling exceeds the critical rate for some of the latter steels.

AUSTENITIZING

The heating of steel above the critical temperature to form austenite is called austenitizing. In addition to the conditions of cooling, the austenitizing conditions control the effectiveness of cooling a steel through M_s with the austenite untransformed. On heating to A_1, the alpha to gamma iron phase change begins, while at A_3 and A_{cm} the ferrite and carbide phases, respectively, are completely dissolved in austenite. Generally, the higher temperatures increase atomic mobility and thus accelerate diffusion and solution of ferrite or carbides. Increased grain growth occurs, and this increases hardenability but decreases toughness and results in more retained (untransformed) austenite, distortion, cracks, and higher residual stresses in the heat-treated steel. Austenite of large grain size possesses increased stability which leads to more retained austenite in the product. High temperatures increase the oxidation of iron and carbon, causing scale which lowers heat transfer on quenching and a decrease in the hardenability of low carbon steel due to carbon loss by diffusion.

Sufficient time at the austenitizing temperature should be allowed for the desired solution of ferrite or carbides and for temperature equalization in the piece. Less time is required after slow heating to the desired temperature, but more time is required for thick pieces. Grain growth increases with both time and temperature.

Optimum austenitizing time and temperature conditions depend on the steel composition and the economical attainment of the diffusional changes desired, as determined by minimizing grain growth, scaling, distortion, cracking, and residual stresses. For hypoeutectoid steels, a temperature just above A_3 is usually preferred, while for hypereutectoid steels temperatures between A_1 and A_{cm} are preferred. Although this results in undissolved carbides in hypereutectoid steels, which decreases hardenability, A_{cm} is so steep that complete carbide solution would allow too much grain growth. Temperature is relatively more important than time in determining austenite grain size.

MASS AND COMPOSITION EFFECT

The center of large sections tends to cool more slowly than the surface. In quenching this results in interior transformations at higher temperatures and at later times as compared with the surface. Thus in low hardenability steels of large section this mass effect predominates, and the thermal gradient in the steel precludes obtaining the high critical cooling velocity required for full hardening. From the S-curve it is seen that quenching at temperatures above M_s often allows more time for temperature equalization, thus decreasing distortion and residual stresses, but the product is softer due to the lower bainite formed.

Carbon and most alloys in steel reduce M_s and increase hardenability. In air-hardening steels transformation is retarded to the point where full martensitic hardness is produced by moderately slow cooling. The effectiveness of alloys depends on the nature of the alloy and on the extent to which they have been dissolved in austenite. The lower cooling rates possible with alloy steels decrease thermal stresses and assist in hardening larger sections. It is possible to lower the carbon content of alloy steels, the decreased hardenability due to reduced carbon being readily offset by the increased hardenability due to the alloy.

QUENCHING

Quenching may be defined as the rapid cooling of an object by the application of cooler media to its surface. When a liquid quench is used, an insulating vapor blankets the piece immediately after immersion, causing slow cooling. This is followed by wetting of the piece by the liquid and violent bubbling, which gives the fastest cooling rate. Finally, the temperature difference between the piece and the liquid decreases until vapor evolution ceases and slower cooling again predominates.

Convection, heat transfer by fluid mixing; conduction, heat transfer without motion of component particles; and radiation, heat transfer by the emission, transmission, and absorption of radiant energy are the heat transfer mechanisms involved. Theoretically, heat transfer rates depend directly on the thermal driving force or potential (temperature difference) and inversely on the resistance to heat flow. In quenching, resistance to heat flow depends on the thermal properties of the metal, its thickness, surface condition and area, and on the physical properties of the quenching medium and its velocity past the metal surface.

The cooling rate required for a given steel austenitized under definite conditions depends on the properties, particularly hardness, required in the finished product. The maximum hardness is fixed by the composition (carbon content), while the thickness of the part and the distortion tendency determine the optimum quenching technique. Thus the ideal quenching medium would cool at the maximum rate past the knee of the S-curve followed by a very slow rate through the martensite formation range to allow temperature equalization in the piece and minimize distortion and residual stresses.

The actual cooling rate depends on:

1. The steel used — its history, grain size, nature

of alloys, carbon and alloy content, and thermal conductivity.

2. The piece quenched – its surface, mass, and complication.

3. Austenitizing – time and temperature, especially the extent of solution of ferrite and carbides, and surface scale and/or decarburization.

4. Temperature potential – difference in austenitizing and quenching temperatures.

5. Quenching medium – its thermal and physical properties.

6. Quenching conditions – temperature and its variation, degree and method of agitation, and heat transfer coefficients, which express the dependency of the cooling rate on such factors as tank geometry and velocity of medium past the metal surface.

7. Required product quality.

If full hardness is required and is not being obtained, the mechanical properties of the finished part will still be inferior to those of fully martensitic steel tempered to the same hardness, and a faster cooling rate is required. The fastest possible cooling rate results when cool quenching medium is in contact with the surface and heat is dissipated as rapidly as it reaches the surface, i.e., when heat transfer is limited by the metal thermal conductivity. Although the most obvious way to get faster cooling is to change to a medium that cools more rapidly, it should be emphasized that *in solid to liquid heat transfer using any fluid, the most important barrier to the flow of heat is the relatively thin film of stagnant fluid on the solid surface.* Heat passes through this film by conduction only. Agitation accelerates heat transfer by scouring off this film, which is particularly important in the early stages of cooling when vapor is present. Increases in cooling rate can be affected by other means, such as reducing scale, which become obvious upon reviewing the factors affecting the cooling rate.

The optimum temperature for quenching a given steel is the lowest temperature that will give the required hardness without excessive distortion and residual stress. The martensite formation range, which usually begins at M_s temperatures of 800 to 400°F., varying with the nature of the alloy and the carbon and alloy content, should be carefully considered in selecting quenching bath temperature.

Work should remain in the quench bath long enough for temperature equalization. If the piece is removed too quickly, distortion, residual stresses, and undesired transformation products in the center of the piece may result. This is particularly important where heat transfer by conduction in the metal limits cooling, as in large sections. Aside from the added expense of quenching too long, austenite may transform to unwanted structures at bath temperatures above the M_s point.

Quenching Processes

The main types of quenching processes are conventional quenching and hot quenching. Conventional quenching involves rapid, continuous cooling to 60-120°F. Hot quenching, as usually applied, involves stopping the cooling at a temperature in or above the martensite transformation range, which is lower than the temperatures at which austenite transforms to pearlite. Transformation then occurs isothermally or during subsequent cooling, being determined by the holding time at quenching temperature before further cooling. Hot quenches are used where conventional quenches do not permit sufficient reduction in distortion and residual stresses or for obtaining steels of special properties. Martempering, austempering, and modifications of these processes are hot quenches.

In *martempering*, steel is cooled rapidly to a temperature in the vicinity of M_s, usually slightly above M_s; the work is held long enough to equalize temperature throughout the section but not long enough for bainite formation; and finally the part is very slowly cooled, usually in air, through the martensite formation range. M_f temperatures are not well established but are believed to be about 150-300°F. below M_s.

In *austempering*, steel is cooled rapidly to and held at a constant subcritical temperature long enough for a completely bainitic structure to form, usually followed by water cooling. Temperatures in the order of 500-800°F. are involved. Depending on the required product characteristics and steels used, several modifications of martempering and austempering processes are being successfully used in industry. The hot oil quenching process is one modification which will be described later. All of these modified processes depend on and may readily be understood from the principles presented above.

Quenching Media

Aside from the fact that it must give the required hardness without excessive distortion, the requirements of a satisfactory quenching medium are shown qualitatively in Table I (See page 102). A comparison of these factors for quenching media in common use is presented. Cooling in still air is usually employed only for high alloy steels in complicated or massive section. The poor heat transfer properties of gases obviate their use for rapid cooling, which is necessary in hot quenching, as it is generally uneconomical to provide large volumes of cool gas to metal surfaces.

The more favorable thermal properties of liquids, as compared with gases, permit satisfactory cooling rates with a variety of these media. It is important to remove gases, primarily from vaporization of the medium but also entering on the work and in the liquid, from the surface of the work, since gases

TABLE I
Summarized Comparison of Quenching Media

Properties	*Ideal Requirements*	*Water and Water Solutions*	*Mineral Oil*[1]	*Air*
1. Cooling rate	Must cool at the desired rate	Fastest	Intermediate	Slowest
a. At knee of S-curve	Minimum rate must equal critical cooling velocity	Very fast	Fast enough for many steels	Too slow for any but special high alloy steels
b. Below knee of S-curve	Cool very slowly	Very fast	Cools much more slowly than water	Cools very slowly
2. Effect of temperature on cooling rate	No significant decrease as temperature rises — increase is desirable	Water cooling rate decreases rapidly as temperature rises; salts are better	Cooling rate improves as temperature rises	Very little effect: still very slow
3. Safety	Safe	Water is safe but some salts explode and caustic is dangerous	Some fire hazard but low with proper oil and precautions	Safe
4. Service life	Long	Caustic solution must be replaced often	Satisfactory with proper precautions	No problem
5. Initial cost	Low	Generally consistent with the results obtained — salt solutions and air currents require special equipment		
6. Cleaning quenched work	Easy	Salts require a water wash	Satisfactory methods are available	No problem
7. Ease of handling	Easy	Difficulty with salts	Easy	No problem in still air
8. Corrosion	None	Salts are corrosive	None	None
9. Drag-out and evaporation loss	Low	Usually low	Low with proper oil	No problem
10. Availability	Good	Good	Good	Good
11. Effect on properties of quenched metal	None	None	None	None

[1]Animal, fish, and vegetable oils are much less widely used than in the past due to inferior odor and oxidation quality.

hinder cooling markedly. Mechanical agitation and circulation of the liquid against the work are the best means of accomplishing this, and at the same time the resulting uniform bath temperature gives uniform hardness and reduces the localized overheating of the medium with gas evolution.

Water or aqueous solutions furnish the drastic cooling rates, approaching the theoretical maximum, required for hardening plain carbon or low alloy steels of low or medium carbon content and of small grain size used for pieces of low mass and simple shape. These steels are called shallow- or water-hardening steels for obvious reasons. They are relatively low-priced and are unsuitable for use when distortion or residual stresses are problems. Water provides the additional advantages of cleanliness, ease of handling, and presents no fire hazard. It should be mentioned that low-carbon steels of fine grain size possess such low hardenability that they cannot be properly hardened by quenching.

While oil will not harden water-hardening grades of steel, it is widely used where a water quench is too drastic and provides uniform quenching for a wide range of alloy steels. In the early stages of cooling, the vapor-blanket and bubble periods, the cooling rate in oil increases while it slows markedly in the final stages – this indicates that for the steels for which it is used, oil comes the closest to meeting the cooling rate requirements of an ideal quenching medium. The cooling rate obtained with oil may be increased not only by agitation but also by careful compounding with selected high quality fatty materials. These steels, called deep- or oil-hardening steels, contain appreciable alloy content which increases hardenability and makes them suitable for thicker, more complicated parts in which the reduction of residual stresses and distortion is important. A properly selected oil for conventional quenching at about 100°F. will have the advantages shown in Table I.

The temperature gradient from surface to center of a part increases with cooling rate. This explains why parts quenched in water are subject to more residual stresses, cracking, and distortion: in addition to the transformation stress resulting from the increase in volume when martensite forms from austenite at the surface, the thermal gradient delays the center transformation and new stresses are then set up when the center transforms. Under these conditions the center is trapped in the hard martensite case already formed at the surface. In oil quenching the thermal gradient is greatly reduced, and the surface and center of the part transform at more nearly the same time, reducing cracking, distortion, and residual stresses.

On the practical side, it is worth noting that quench bath temperature variation is much less critical with oil than with water. This simplifies control and assures a product of uniform quality.

Special quenching methods for very close tolerances include cold die quenching and the use of quenching presses. In the former method the part contacts a cooled solid surface, while in the second method the piece is held to eliminate distortion while it is quenched with a liquid medium.

While methods have been developed for the calculation of hardenability, current practice usually involves the experimental determination of this factor for each steel, using methods such as:

1. The Jominy End-quench Tests for medium-hardening or common alloy steels.

2. The Rockwell-Inch Test for shallow-hardening steels.

3. The air hardening test for deep-hardening alloy steels.

Grossman's severity of quench test is a metallurgical method which has been proposed for the evaluation of quenching media.

Such a wide variety of types of equipment for quenching is available that no discussion of this subject will be given here, except to note that the essential elements of a large system include the quenching tank and medium, equipped with means for agitation, coolers, heaters, strainers, instruments, pumps, supply tank, handling facilities for parts, and ventilators and safety equipment. Information on these and smaller systems, to fit the needs of any particular plant, is readily available.

TEMPERING

Tempering is usually preceded by air cooling to room temperature for all steels except some very high hardenability types which may require furnace cooling. If steel is reheated to the tempering temperature before all of the austenite has transformed to martensite, the structure after tempering tends to be a mixture of either tempered martensite and bainite or tempered and untempered martensite, the untempered martensite forming from retained austenite on final cooling to room temperature. Alternately, in high carbon alloy steels retained austenite may be stabilized so that it will not form martensite on final cooling. Thus the value of cooling as-quenched steel to room temperature (or M_f) before final tempering is obvious, because retempering and special treatments to transform stabilized retained austenite are unnecessary. The importance of this cooling in obtaining uniform and maximum physicals with maximum reductions in retained austenite, residual stresses, and distortion should be emphasized.

Tempering involves the heating of steel to subcritical temperatures to relieve quenching stresses and recover some degree of toughness and ductility without losing significant hardness. At temperatures up to about 450°F., the decrease in hardness

is slight, while much greater stress relief and toughness results. These results are obtained by the precipitation of carbides from unstable martensite and by diffusion and coalescence of the carbides. Appreciable precipitation of carbides begins at about 200°F. At about 450°F. most of the carbides have precipitated, and marked transformation of retained austenite to martensite occurs. Further heating tempers this martensite, and at about 550°F. significant coalescence of cementite begins. The resulting dispersion of essentially spheroidal particles in more stable martensite is entirely different from pearlite. At higher temperatures these spheroids become larger, and the steel becomes softer and more ductile.

Time is an important tempering variable. Steels are usually tempered at least one hour for each inch of thickness and as soon as possible after conventional quenching for prompt stress relief and to avoid cracking.

Alloy steels are more resistant than plain carbon steels to softening during tempering. This permits tempering for longer times and/or at higher temperatures for increased stress relief, which is particularly important in larger sections.

For optimum physicals, a given steel should not be tempered to a hardness below its intended working range. Usually when less hardness is desired, a better combination of toughness, ductility, and hardness can be obtained from lower alloy steel. In this connection, hardness is a common, although not exact, index for wear resistance. Thus it is seen that tempering is almost as important as quenching in determining the quality of heat treated parts.

Some steels exhibit a decrease in toughness as well as hardness when tempering in the 400-700°F. range, and a second decrease in toughness, called temper-brittleness, may be noted when tempering at 850-1100°F. and above. The 400-700°F. range is usually avoided for these steels, and temper-brittleness may be avoided by tempering below this range or cooling (quenching) rapidly through this range of temperature.

Tempering Media

Tempering is usually practiced by heating in liquid media such as oil, salt, or melted metal (lead) in immersion pots or in air in carefully controlled furnaces. Tempering in air is frequently used for high-temperature furnace tempering of complicated shapes in which hot liquid might cause undesirable initial stresses. Air is usually circulated by fans to increase its low cooling rate. Molten salt and molten lead, in addition to air, are often used for high temperature tempering, especially for alloy steels, where their particular properties are desired.

For the development of the desired structure, uniform heating at the tempering temperature for a definite time is necessary. The ease of temperature control and the uniformity of heating obtained make liquids particularly suited for low temperature, 300 to 500°F., tempering. As no transformation is involved in cooling, the cooling rate has no effect on hardness. Salts may be used at much higher temperatures than oils, but oils are much easier to handle and are non-corrosive.

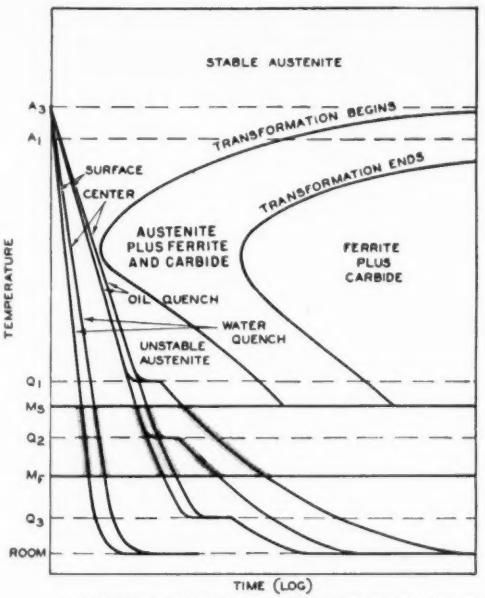


Figure 3 — Cooling Curves for Hot Oil Quenching.

A suitable oil will possess good thermal and oxidation stability which will give long service life. Its flash point should be high and at least 50°F. above the tempering temperature to insure against fire hazard, smoking, and excessive consumption due to evaporation. Its resistance to deterioration should be high to avoid sludging and coking. Carbon is a non-conductor of heat and can cause local hot-spots and burn-outs in tempering pots. Pots should be cleaned and inspected periodically to avoid costly burn-outs. A good oil will not develop objectionable odors or excessive smoke on use. If cleaning is necessary, oil may readily be removed from the work, otherwise a rust-resistant oil film is provided.

Before leaving the subject of tempering, it should be mentioned that martensite undergoes a self-tempering during quenching, with the carbide precipitation which occurs on tempering. Since this self-tempering increases as the cooling rate decreases, the desirability of very slow cooling through the martensite formation range is evident.

HOT OIL QUENCHING

Process

Hot oil quenching involves quenching steel into

mineral oil at 200-400°F. and holding for temperature equalization, followed by very slow cooling in air to room temperature. From the preceding discussion, it is clear that depending on the M_s temperature of the steel, three basically different types of quenching are involved, as shown in Figure 3. When the bath temperature is near or slightly above M_s (See Q_1) true martempering, such as has been described, is obtained, provided the holding time does not permit transformation to lower bainite. When the bath temperature falls within the martensite formation range (see Q_2), a modified martempering operation results, since martensite formation has not been completed. Depending on the bath temperature, a good proportion of the advantages of martempering can result, since much of the steel is still in the plastic austenitic condition, allowing stress relief and reducing distortion, cracking, and retained austenite. Additional advantages are gained:

1. reduction in thermal gradient in the piece above the martensite range (as in martempering) due to slower cooling, and
2. bainite will not form during holding for temperature equalization, as is possible in martempering. This is an advantage where thicker sections are involved and where the hardness required will tolerate no bainite.

If the bath temperature is below the martensite range (see Q_3), the reduction in the thermal gradient in the piece above and through the martensite range and the freedom from possible bainite formation are still worthwhile advantages, promoting uniform hardness in the quenched work and obtaining some of the advantages of martempering.

Thus it is readily seen that constant temperature hot oil quenching may be equivalent to martempering. If martempering does not result, differing degrees of the advantages of martempering may nevertheless be obtained, along with the additional advantage of freedom from possible bainite formation. All of these quenches are definitely advantageous when used for suitable steels. Specific results with a given steel depend especially on factors affecting M_s and also on the steel used, the part quenched, austenitizing conditions, and the quenching operation — its conditions and their control, the oil medium, and the equipment employed. The importance of final tempering is clear.

Oil Medium as Compared with Salts

Salts are widely used for martempering and austempering because they give a satisfactory cooling rate and service life at the high temperatures necessary for these processes. While salts can also be used for hot quenching, it is preferable to use hot oil for the many steels of sufficient hardenability in order to avoid the undesirable features of salt media. Most salts are solid at room temperature, plugging small openings and making the work and equipment hard to clean. Salts are difficult to handle and require special equipment: their corrosiveness also appreciably shortens equipment life.

A properly selected oil is easy to handle and requires relatively little special equipment; is noncorrosive; the work is relatively easily cleaned if the rust protection provided by the oil film is not needed; with proper precautions, a satisfactory service life can be obtained and the fire hazard is small; losses due to "drag out" and evaporation are low; and the cost is moderate for the results obtained. Some of these advantages are not as pronounced during the last stages of use, depending on the service and installation.

The cooling rate with oil improves as the temperature increases while the rate with salts shows an undesirable decrease. The decrease in oil viscosity with temperature rise results in more rapid dissipation of heat. Conventional quenching experience indicates that the decreased cooling rate with oil in the final stages of cooling is very desirable for reducing distortion, cracks, residual stresses, and retained austenite. In view of the close approach of oil to the ideal quenching medium and because higher viscosity hot quenching oils may give faster cooling rates in the early stages of cooling than conventional quenching oil, it is indicated that, for steels of sufficient hardenability, oil is preferable to salts for hot quenching on the basis of cooling rate considerations, particularly where martempering is not involved, i.e., at Q_2 and Q_3 of Figure 3.

The significance of unused oil tests in hot quenching operations is summarized in Table II. In connection with the Flash Test, it is of interest that the autogeneous ignition temperature, the oil temperature which causes ignition in the absence of a flame, is 750°F. or higher for good hot quenching oils. Thus at current hot quenching temperatures of 200-400°F., the oil is not hot enough to support combustion. The flames that occur when hot parts are quenched are quickly extinguished because most of the oil is at 200-400°F. It is advisable to exercise caution in comparing oils on the basis of viscosity at temperatures lower than bath temperatures. The significant viscosity is the value at bath temperature, and undue emphasis on viscosities at other temperatures can be misleading.

Judgment should be exercised when interpreting data from stability tests, such as oxidation tests. A wide variety of these tests are available, but test reproducibility is frequently poor. It is also obvious that the test conditions used are in many cases not equivalent to service conditions.

Equipment

Hot oil quenching may be conducted on a large

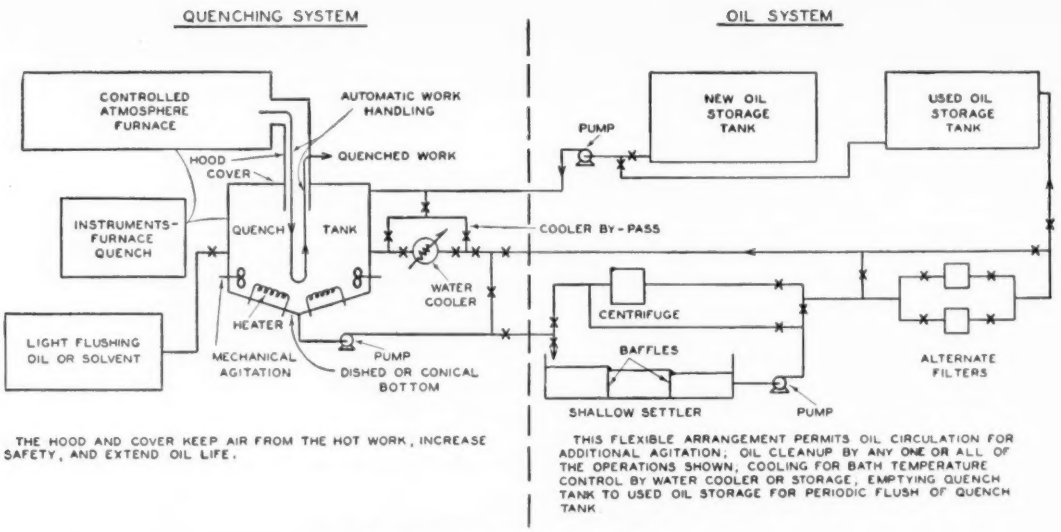

QUENCHING SYSTEM
OIL SYSTEM
CONTROLLED ATMOSPHERE FURNACE
AUTOMATIC WORK HANDLING
HOOD COVER
QUENCHED WORK
INSTRUMENTS-FURNACE QUENCH
QUENCH TANK
WATER COOLER
HEATER
LIGHT FLUSHING OIL OR SOLVENT
MECHANICAL AGITATION
PUMP DISHED OR CONICAL BOTTOM
PUMP
NEW OIL STORAGE TANK
USED OIL STORAGE TANK
COOLER BY-PASS
CENTRIFUGE
BAFFLES
SHALLOW SETTLER
PUMP
ALTERNATE FILTERS
THE HOOD AND COVER KEEP AIR FROM THE HOT WORK, INCREASE SAFETY, AND EXTEND OIL LIFE.
THIS FLEXIBLE ARRANGEMENT PERMITS OIL CIRCULATION FOR ADDITIONAL AGITATION; OIL CLEANUP BY ANY ONE OR ALL OF THE OPERATIONS SHOWN; COOLING FOR BATH TEMPERATURE CONTROL BY WATER COOLER OR STORAGE; EMPTYING QUENCH TANK TO USED OIL STORAGE FOR PERIODIC FLUSH OF QUENCH TANK

Figure 4 — Hot Oil Quenching System.

Courtesy International Harvester Company

Figure 5 — Commercial Hot Oil Quenching Installation.

or small scale in a variety of types of equipment, including continuous, batch, and fixture units. It is possible that many existing quenching systems can be readily converted to hot oil quenching. Figure 4 illustrates some of the many possible variations in a well-appointed, continuous, hot quenching system. The particular equipment required will depend on the exact service and installation size. Note that the principal equipment elements are the quenching tank, equipped with heaters, coolers, agitation, instruments, cover, and provisions for cleanup; means for handling the work into and out of the bath; equipment of adequate capacity for handling oil and for cleaning the system as described in the note under Oil System; and safety fire equipment. The economical cleanup of used quenching oil should be carefuly considered.

Figure 5 is a photograph of a good commercial installation and shows a tray of transmission countershafts ready to enter quench bath.

Operation

For a given steel part, austenitized under definite conditions, the most important hot quenching variables directly affecting product quality are time, temperature, and agitation. The importance of these factors has been discussed: only a summary of their effects in hot oil quenching will be presented.

If quenching time is too short, full equalization of temperature in the work will not be obtained: if a piece is quenched too long, production is slowed and, in martempering, bainite may be formed. The optimum quenching time is necessary to meet uniformly product physicals and minimize distortion, cracks, residual stresses, and retained austenite. Hot quenching times of 8 minutes maximum are involved in present commercial practice.

The discussion of oil life in the next section will clearly show that the optimum quenching temperature, which must not be so high that satisfactory hardness is not obtained, is a compromise between oil life and reduction of distortion and cracking. These relations are presented for a hypothetica

TABLE II

Significance of New Oil Tests in Hot Oil Quenching

1. Flash and Fire Tests	Values should be sufficiently high to reduce fire hazard and prevent excessive evaporation of oil which may affect cooling rate adversely in the initial stages of cooling, and promote excessive oil losses. A Flash Test 100°F. above the hot bath temperature should provide an ample margin of safety, although the exact requirement will depend on the equipment and service.
2. Viscosity Tests	The viscosity at bath temperature should be low enough to assure ease of agitation and rapid dissipation of heat, fast cooling and low consumption due to good drainage from the quenched parts.
3. Pour Test	Pour quality is of no concern once the oil is placed in service. In cold weather it is of importance in handling oil from drums, tank cars, and storage tanks.
4. Stability Tests	A good oil will possess good thermal, catalytic, and oxidation stability. In the various tests used to measure this quality, care must be taken in interpreting data to avoid confusing evaporation with viscosity rise caused by oil deterioration.
5. Saponification Number	A low value assures that fatty materials, commonly used to increase quenching rate of conventional oils, are not present. These fatty materials generally are unstable at hot quenching temperatures.
6. Inspection	The oil should be of uniform clear color and free of foreign materials.

The interpretation of tests will depend to a very great extent upon experience since it has been found that hot quenching oils cannot be chosen entirely upon the basis of results of bench tests. Such tests can, at best, only serve as a screen for choosing products for actual performance testing.

case in Figure 6. While satisfactory hardness is not obtained at bath temperatures over 350°F., a satisfactory reduction of distortion and residual stress is obtained at 300°F., permitting a substantial gain in oil service life by quenching at 300°F. (increment AB). Present commercial practice indicates maximum temperatures required to be about 400°F. The importance of temperature control for uniform product hardness is acknowledged by commercial practice, being considered good if the bath is automatically controlled to within ±5°F. Good mechanical agitation and adequate circulation rates and cooling facilities are very effective for controlling temperature.

It is natural for the metallurgist, who considers martempering as the primary means of reducing distortion, to experiment with temperatures too high for hot quenching with the result that satisfactory hardness is not obtained. A preferred approach would be to start at about 200°F. and progressively try higher temperatures to determine the maximum temperature giving the required hardness and then evaluating the reduction in distortion and residual stresses obtained. Good agitation is vital to the success of such experiments.

Good agitation is a prime requirement for uniform product quality, especially hardness. The bath should be agitated constantly during quenching to assure high oil velocities past the work surface as has already been emphasized. Agitation may be provided by mechanical means or by circulation, preferably by both methods, and is importantly related to the tank geometry.

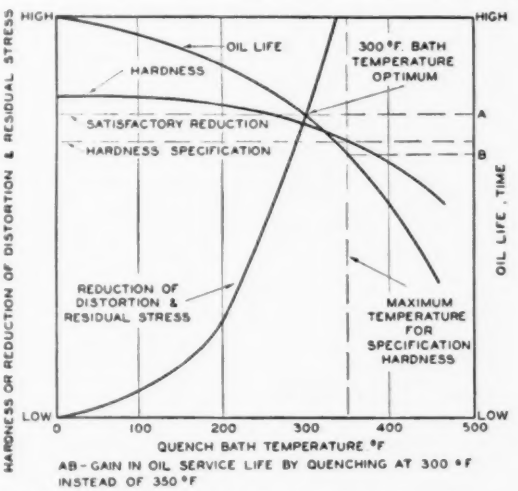


Figure 6 — Optimum Hot Oil Quenching Temperature.

Oil Life

Oil life in service depends on the ability of the oil to withstand chemical decomposition, the service conditions, especially temperature, and the presence of catalysts.

The chemical decomposition of quenching oil is

indicated to be due mainly to oxidation and polymerization. Oxidation is promoted by the contact of air with oil at high temperatures for long times in this process. The hydrocarbons of the oil progressively form acids, resins, varnish, lacquers, carbonaceous material, and finally coke. Polymerization of oil and oil oxidation products consists essentially of molecules of these materials linking up to form still heavier molecules. In the final stages of oil service life these materials (sludge) deposit on the work and make cleaning more difficult.

The significance of used hot quenching oil tests is outlined in Table III. When oil is exposed to the adverse conditions encountered in the hot quenching operation, the viscosity, neutralization number, ash and sludge content of the oil generally increase. Due to catalytic effects, the changes in test values are accelerated in the final stages of use, and sharp increases, especially in viscosity, may result.

The principal factors affecting oil life, i.e., causing sludging and deposits, are discussed below:

1. *Temperature.* An 18°F. temperature rise increases the speed of chemical reactions two to four times. This effect is more pronounced at higher temperatures and leads to "chain reactions". Thus the lowest temperatures giving satisfactory hardness and distortion reduction are much to be preferred for economical hot quenching. The importance of good agitation in preventing hot spots is clear. To prevent startup delays for heating the oil after short down periods and at the same time to retard chemical decomposition of oil and to save on heating costs, it is suggested as a compromise that the oil be allowed to cool to a temperature just above the boiling point of water. Gradual oil heat-up and agitation help to avoid hot spots.

2. *Ratio of Oil to Steel.* While it is obvious that a very low oil life will result if steel is quenched at a high rate in a small tank of oil, it is also true that a large tank is not necessary to quench steel at a low rate. Large oil baths allow operation for longer periods between oil changes and hence increase production, reduce the cooling and ventilation requirements but require more power for agitation and more heat on startup. While ratios of one to two gallons of oil per pound of steel quenched per hour are customary for conventional quenching at 80-120°F., the currently best commercial practice uses a ratio of two to three gallons of oil per pound of steel quenched per hour for hot quenching. Depending on the process and installation details, it is indicated that ratios of 2 to 3 gallons of oil per pound of steel per hour should give an oil life of about 5 to 6 months.

3. *Oil quality.* Superior oils for hot quenching give the best oil life. Oil quality depends on the refinery stocks used and the degree and types of refinery processing employed in manufacture.

4. *Catalysts.* The presence of air, sludge, water and certain metals, such as copper, accelerates oil deterioration by increasing the chemical decomposition reaction rates. The most undesirable metals are usually not present in the quenching system. Air is essential for oxidation reactions to occur, and the importance of the exclusion of air from contact with the hot oil is recognized in good practice by providing quench tank covers and enclosing the hot work. Water is vaporized at hot quenching temperatures, but its presence in the oil system is undesirable. The effect of sludge is indicated by the data of Table IV. While the quality of new oil is adversely affected, the large increases in viscosity

TABLE III

Significance of Used Oil Tests in Hot Oil Quenching

1. Viscosity Tests	The viscosity increase of the used oil, compared with new oil, is indicative of the extent of oil deterioration and evaporation which has occurred.
2. Neutralization Number	The rise in neutralization number is an indication of the extent of oil deterioration which results in the formation of acid oxidation products.
3. Ash Content	Ash content of used oil is an indication of the extent of metallic contamination.
4. Sludge Content	A measure of the extent of sludge formed from deterioration and contamination. Low values are desirable.
5. Odor	Oil normally develops an oxidized or burnt odor with use. Any abnormal odor may serve as a clue in "trouble shooting".
6. Inspection	Visual inspection may be of assistance in predicting suitability of oil for further use.

The tests shown above are only a few of the tests which might be of significance in a particular case. Choice of other tests would, of course, depend upon types of problems encountered in service. Test interpretation will require a knowledge of the conditions to which the oil has been exposed and its normal behavior under such conditions. Too great reliance should not be placed upon any one test, since each must be considered in its relationship to other values.

and sludge in the used oil from the accelerated oxidation test clearly show the advantages of retarding the formation of and removing sludge while the oil is in service. The desirability of thoroughly cleaning the quench tank and system between batches of oil is also clear. Aside from decreasing oil life and depositing on the work, making it more difficult to clean, sludge may retard quenching rates and interfere with heat transfer by depositing on the cooling and heating equipment.

5. *Oil Make-up.* As already pointed out, drag-out and evaporation oil losses are low with a good hot quenching oil. Commercial practice indicates make-up requirements to be low and approximately the same as for conventional oil quench. Make-up oil should be added uniformly and regularly. Experience in many types of service has shown that if new oil is added to partially oxidized oil in excessive amounts, insoluble sludge may be thrown down (precipitated) by the oil. Make-up oil addition should never exceed 10% of the bath volume. It is preferable to add smaller amounts each shift.

6. *Oil Cleanup.* The economics of the installation determine how much oil cleanup is justified. Since a previous issue of LUBRICATION (January, 1947), "Oil Purification, Filtration, and Reclamation", has dealt with this subject, it will suffice here to point out that gravity settling and centrifuges remove insoluble particles and insoluble sludge, while activated clay filters, hot activated clay filters, and chemical treatment plus hot activated clay treatment remove these materials and also remove soluble deterioration products (acids, resins). The extent of removal depends on the specific equipment and procedure used. It is desirable to operate the oil cleanup system continuously and at a sufficient rate. It is advantageous to operate this system at least some of the time while not quenching, using agitation in the quench tank to facilitate removal of settled solids.

7. *System Cleanup.* It is desirable to agitate hot solvent or a light flushing oil in the quench tank and system for the best sludge removal possible. A used oil storage tank makes it possible to periodically clean the system between oil changes.

8. *Size and Complication of Piece.* Since higher viscosity oil will still afford a satisfactory cooling rate for smaller, simpler pieces, it is obvious that longer oil service life will result, since the oil can be used up to higher end viscosities.

In present commercial practice the oil discard point is determined by:

1. Hardness tests — oil is discarded when hardness drops below the required level.
2. Deposits on work — discard oil when pieces become too difficult to clean.
3. Viscosity rise to an arbitrary point — discard oil here because other tests have correlated oil viscosity with hardness of piece or deposits.
4. Viscosity plot — discard oil when a plot of viscosity versus steel throughout indicates that the viscosity will rise rapidly and very soon.

For hot quenching bearing races, transmission gears, and saws, commercial practice in good installations has given two to seven months oil life, varying with the service and the oil life factors.

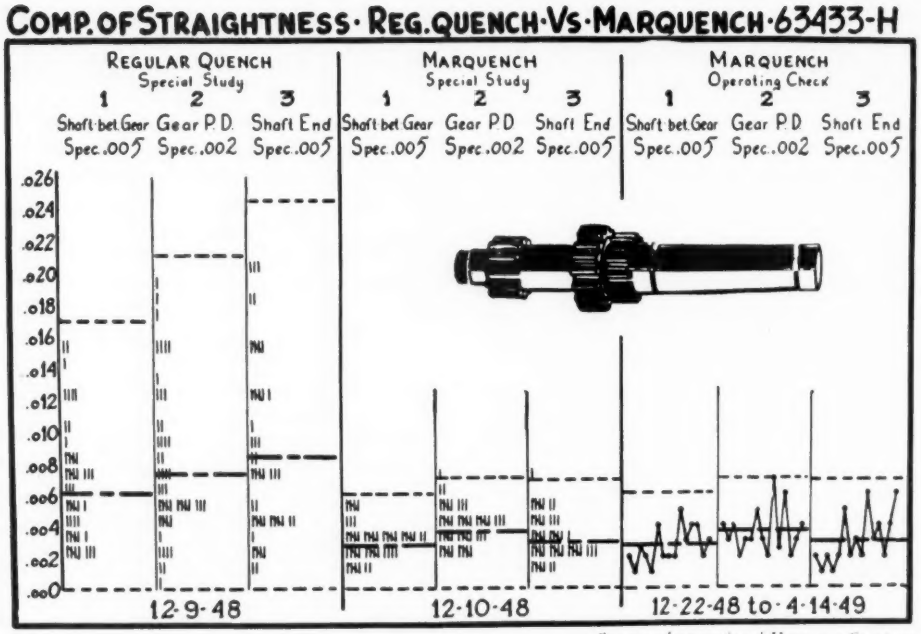
Finishing

Six hours of air cooling is generally sufficient to complete the martensite transformation in the quenched part. In comparison to the advantages resulting from hot oil quenching, the necessity for

TABLE IV
Effect of Sludge on Oxidation Stability

Blend	*1*	*2*	*3*
Composition, % Vol.:			
New Oil	100.0	99.0	95.0
Sludge*	0	1.0	5.0
Tests			
Viscosity, SSU @ 210°F.	98.6	98.9	101.7
Neutralization No.	0.05	0.05	0.17
Soluble Deterioration Products, mg/10g	4	9	21
Naphtha Insolubles, mg/10g	0	10	49
Accelerated Oxidation Test**			
Used Oil tests:			
Viscosity, SSU @ 210°F.	152	157	288
Neutralization No.	3.0	3.1	3.2
Soluble Deterioration Products, mg/10g	385	451	815
Naphtha Insolubles, mg/10g	35	60	364

*Highly oxidized material from service tank at discard, 2400 viscosity SF at 210°F.
**168 hours at 341°F., air rate 10 1/hr.



Courtesy International Harvester Company

Figure 7 — Conventional versus Hot Oil Quenching — Distortion comparison at three points on shaft of transmission countershaft.

cleaning from the pieces the deposits of oxidized material from the used oil has been considered a minor inconvenience. Cleaning methods used include spraying the work with an oil solvent followed by an alkaline spray, tri-sodium phosphate type sprays, and hot water rinsing to float off the oil. Where it is safe and adequate ventilation is available, kerosine or safety naphtha washing affords one of the best cleaning methods. In all cases, any carbon remaining on the work is removed by conventional tempering for recovery of toughness and ductility, already described, at 300-350°F. for 1-2 hours per inch of thickness.

Results

In ball and roller bearings and gears, hardness is directly related to wear and hence life of the part. Full hardness is essential in bearings and differential and aeronautical gears where impact and toughness are of lower importance. Impact due to clash of gears is a factor in transmissions, and slightly lower hardness is in order. In the Rockwell Hardness Test, values of C62 to C65 correspond to full or "file" hardness. File hardness is determined with specially hardened steel files.

Commercial hot oil quenching at 300-330°F. allows Rockwell hardnesses of C63 to C65 to be regularly obtained on as-quenched outer bearing races. Heavy duty transmission gears meet hardness requirements, Rockwell values of C62-65 being obtained on the as-quenched gears after quenching at 350-400°F. Rockwell C60 hardness is obtained on as-quenched lighter-duty gears after 335°F. quench. Saws and saw parts present no hardness problems, Rockwell C50+ being easily obtained after 250-400°F. quench. Hardness values of Rockwell C62-65 have been obtained on 2½ inch sections of suitable alloy steels.

W. Olsen and G. Nevins reported data (*Steel*, December 15, 1947) indicating that distortion can be controlled by adjusting the bath temperature:

Precision Die Steel
1.0% C, 1.1% Mn, 0.5% Cr, 0.5% W, 0.2% V
Austenitized at 1475°F.

Quench	*Per cent Martensite Formed in Bath*	*Average Growth in ¾x3x4" Plate** Solid, in./in.	Bored, 2" hole, in./in.
400°F. Salt	0	0.0010	0.0012
290°F. Oil	65	0.0005	0.0001
85°F. Oil	Nearly 100	0.0009**	0.0002

*Measured after plates tempered at 400°F. to Rockwell C60.
**Warped.

Conventional quench produced high distortion, and in martempering near M_s the thermal stresses were equalized and transformation stresses caused distortion. The minimum distortion occurred at 290°F. where thermal and transformation stresses, which may tend to oppose each other, are balanced. Relatively little information of this type is available, but these data clearly show about 50% reduc-

tion in distortion at 290°F. as compared with conventional quenching at 85°F.

Some very interesting information on the reduction of retained austenite by hot oil quenching as compared with conventional quenching may be found in an article by H. E. Boyer (*Iron Age*, July 3, 1947).

In commercial hot quenching practice, distortion reductions of 40 to 95% have been obtained. The important point here, however, is the fact that the finished pieces have been within allowable tolerances in many cases, and the distortion in the pieces not meeting tolerances is markedly reduced. This is particularly important for gear teeth where the undesirable grinding after heat treatment is eliminated or reduced so that the teeth are not affected. Hot quenching greatly increases production due to the greater output per furnace made possible by the elimination of the necessity for plugs, fixtures, and quenching presses. The great reduction in rejects due to the reduction or elimination of distortion and cracking gives a large saving in material, and subsequent assemblies are made much easier by the better fits obtained. This is very advantageous in the manufacture of tools, bearing races, and gears. In some cases it has been found possible to reduce tolerances before quenching, saving additional material and labor and time in subsequent finishing operations.

The Fort Wayne Works of International Harvester Company report that in a cluster gear 2½ inches in diameter by 15 inches long distortion was reduced from 0.060 inches to within an allowable tolerance of 0.003 inches for 95% of the gears, and the remaining gears were out 0.005 inches maximum. Previously, with conventional quenching, all of these gears were cold straightened, often distorting the gear teeth. Figures 7, 8, 9, 10, and 11 present additional information developed by these workers.

W. B. Cheney and W. C. Hiatt report (*Steel*, Feb. 12, 1951): "Marquenching produced gears with a minimum of residual stress, thereby increasing their service life from 100 to 200 per cent and increasing the load-carrying capacity from 15 to 20 per cent as determined by dynamometer testing"

Applications

References have already been made to some parts which are hot oil quenched commercially. Hot oil quenching is particularly applicable to many of the hardenability steels: high carbon or carburized steels, alloy steels of medium (0.3-0.6%C) or high (0.6-1.0%C) carbon content, and alloy tool steels.

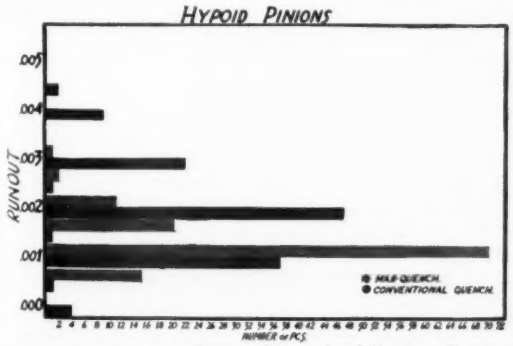
Carburizing is a case-hardening treatment given steel in a carefully controlled furnace in which carbon diffuses into the metal, surface to center. In convenient activated gas carburizing, the furnace atmosphere is controlled to eliminate decarburizing. By carburizing, a steel otherwise unsuitable, such as a low alloy steel, may be case-hardened by suitable heat treatment. Tempering at 300-500°F. is effective in toughening the case and relieving strains while hardness drops off only slightly. Carburizing, hot oil quenching and tempering are very effectively used for commercial gear manufacture.

Commercial hot oil quenching practice includes steels of these types:

Steel	*Composition, %*
SAE 5140 (for oil hardening gears)	0.4C, 0.8Cr
E52100 (for bearings)	1.0C, 1.2-1.5Cr
SAE 4620 (carburized, for gears)	0.2C, 1.83Ni, 0.25Mo
SAE 4820 (carburized, for gears)	0.2C, 3.5Ni, 0.25Mo
SAE 8620 (carburized, for gears)	0.2C, 0.55Ni, 0.5Cr, 0.2Mo
SAE 4320 (carburized, for gears)	0.2C, 1.83Ni, 0.5Cr, 0.25Mo

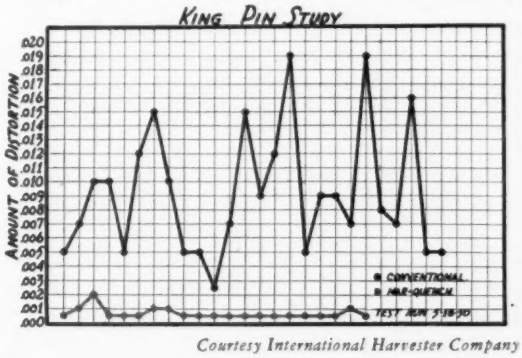
M_s data may be found in the literature for these and other suitable steels.

Although differential gears must be fully hardened and subsequent lapping makes distortion less important, nevertheless experiments are now in progress which indicate that there is a good possibility that hot oil quenching may be successfully



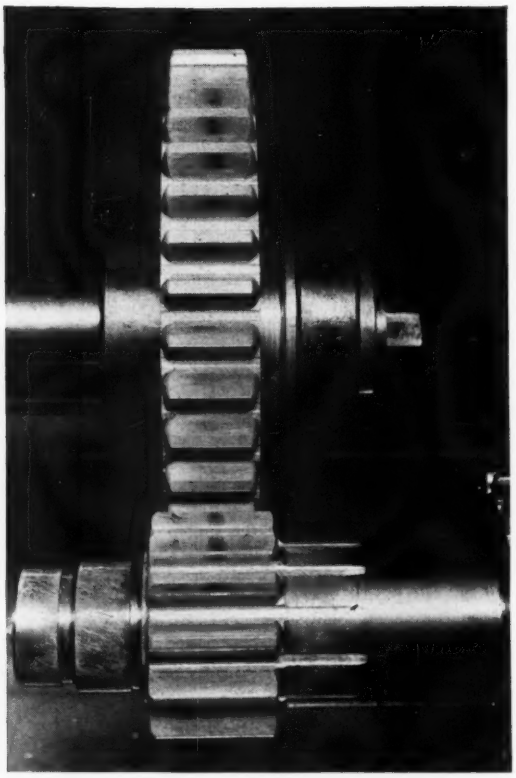
Courtesy International Harvester Company

Figure 8 — Comparison of King Pin Distortion — Conventional versus Hot Oil Quenching.



Courtesy International Harvester Company

Figure 9 — Hypoid Pin Run-out Comparison — Conventional versus Hot Oil Quenching.



Courtesy International Harvester Company

Figure 10 — Hot oil quenched first speed gear showing tooth bearing. Before hot oil quenching these gears were individually tube quenched or die quenched.

used in their manufacture.

It is necessary to case-harden aeronautical gears by nitriding, a very slow process. These gears must be fully hard and free of distortion. While the alternate method of conventional quenching of carburized gears in dies gives too much distortion, the possibility of hot oil quenching carburized gears in dies, i.e., Gleason-type die machines, appears very interesting.

Generally, although the thermal properties of conventional and hot quenching oils differ, it appears that hot oil quenching could be applied to most steels that are conventionally oil quenched at present, providing the advantages gained justify the added cost.

Summary of Advantages and Disadvantages

Hot oil quenching, compared to conventional quenching, requires more equipment, greater safety precautions, cleaning of the work during the latter stages of oil life and is limited with respect to the size, shape, and types of steel that can be quenched to full hardness. Unless distortion or residual stresses are problems, it may not be desirable to use a hot oil quench.

Courtesy International Harvester Company

Figure 11 — Dynamometer Test Results.

The process is, however, applicable to a wide range of important steels. For the many cases in which satisfactory hardness can be obtained, it gives improved control of dimensional changes by reducing or eliminating distortion, and increased service life and load-carrying capacity of the parts result from reduced residual stresses.

Production-wise, hot oil quenching greatly increases the output per furnace due to: elimination of plugs, quenching presses and fixtures; elimination or reduction of finishing operations; large reductions in rejects; and expediting subsequent assembly. Reduced tolerances before hot quenching may also be possible.

SUMMARY

The physical properties of a given part depend on the steel used and its heat treatment, which consists of austenitizing or carburizing, quenching, and tempering for the steels discussed herein.

Current quenching and tempering practice has been reviewed. Hot oil quenching has been discussed in detail to clarify its present and potential commercial applications. Hot oil quenching is especially important today, particularly when used with carburizing, because its use may permit substitution of carbon or low alloy for high alloy steels.

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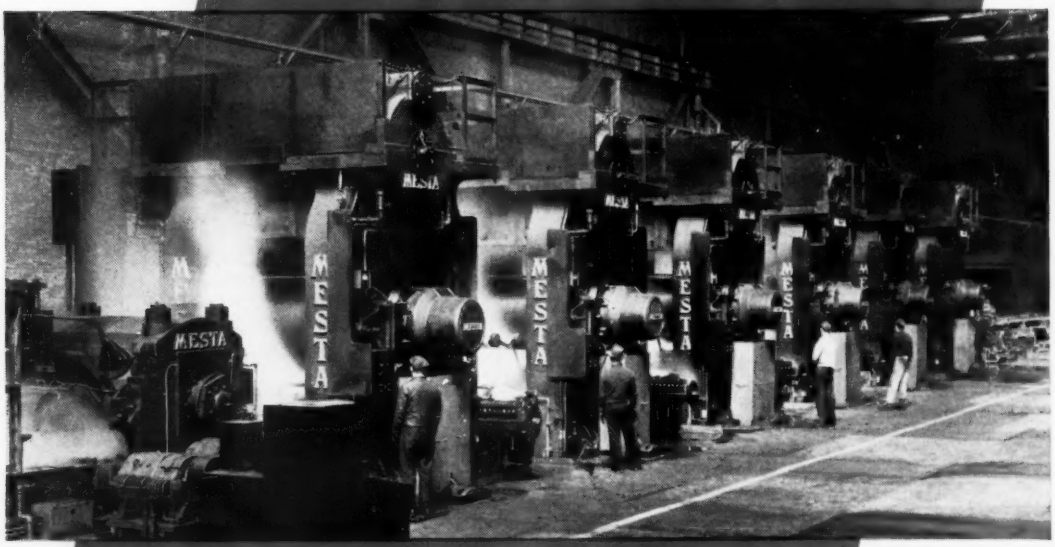

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